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Field Calibration of a Multisensor Capacitance Probe for Des Moines Lobe Soils

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***Abstract**. Measurement of water content in the soil profile is essential for evaluating soil water dynamics. Capacitance sensors detect the soil permittivity (ε) which can be converted into volumetric soil water content (θ_v) by equations. The relationship between θ_v and ε is usually set by default parameters from the manufacturers, but field calibration would be expected to increase the accuracy of the soil moisture measurement instruments. The purpose of this study is to determine the necessity of a field calibration and to evaluate the efficiency of field calibration for the PR2 capacitance probe (Delta-T Devices Ltd., 2004) for Des Moines Lobe soils in north-central Iowa. In this study, the calibration was conducted by fitting the linear equations between ε measured by a PR2 probe and θ_v observed by soil sampling using one-year (2006) and two-year (2006+2007) data for each of 36 locations at 3 depths. The calibrated equations by the one-year data, DeltaT-calibrated-2006 equations, and the two-year data, DeltaT-calibrated-2006+2007 equations, are presented. The predicted soil moisture by the equations were compare with observed soil moisture by four statistical factors, Root mean square error (RMSE), Coefficient of Mass Residual (CMR), Index of agreement (IoA), and Model Efficiency (EF). In predicting the soil moisture in 2006+2007, the results showed that RMSE, CMR, IoA and EF values for DeltaT-default equation were 0.097cm^3 cm^{-3}, -0.092, 0.674 and -1.625, which indicated an unsatisfactory performance compared with the RMSE (0.027 cm^3 cm^{-3}) from Huang et al. (2004). After field calibration, the statistical factor values were 0.053 cm^3 cm^{-3}, 0.033, 0.818, and 0.207 for DeltaT-calibrated-2006 equations, and 0.034 cm^3*

cm^{-3}, 0.000, 0.895 and 0.674 for DeltaT-calibrated-2006+2007 equations. The results showed that the field calibration improved the performance of PR2 Probe in soil moisture measurement, and the two-year calibration equations, DeltaT-calibrated-2006+2007 equations, resulted in the best prediction which was comparable to the result from literature (Huang et al., 2004).

Keywords. PR2 capacitance probe, field calibration, Des Moines Lobe soils.

Introduction

Measurement of water content in the soil profile is essential for evaluating soil water dynamics. With the exception of the traditional thermal-gravimetric method, instruments have been developed for soil moisture measurement involving electromagnetic induction, radar penetration, capacitance measurement, neutron scattering and gamma ray attenuation (Topp and Ferre, 2002). Neutron scattering and capacitance measurement are the methods that allow users to measure water content in the soil profile through an installed access tube, which is less destructive or laborious. Neutron scattering gage has been shown to have satisfactory accuracy and high precision, however, due to the radioactivity of neutron, reasonable attention should be paid to safety rules supplied by the manufacturer (Gardner, 1986). Capacitance sensors have been considered as an alternative for neutron scattering gage due to their advantage to human health.

Capacitance sensors detect the soil moisture by measuring the permittivity (dielectric constant) of the soil either by inserting electrodes into the soil (Chernyak, 1964; Gaskin and Miller, 1996) or lowering sensor(s) into access tubes (Dean et al., 1987; Whalley et al., 1992) based on the large difference in permittivity of water (80 at 22ºC), minerals(4-5) and air (1). Advantages of the capacitance sensor measuring water content through the access tube are: easily recorded by automatic logger, cheaper, reading can be obtained instantly without random counting error, no nuclear hazard, and axial sensitivity (Bell et al., 1987). A multisensor capacitance probe integrates multiple sensors on an extended rod that can get volumetric soil water content at multiple depths one time through an access tube (Evett and Stiner, 1995; Paltimeanu and Starr, 1997; Ployakov et al., 2005; Evett et al., 2006).

The Profile probe (PR1 and PR2, Delta-T Devices Ltd., Cambridge, UK) is a newly manufactured multisensor capacitance probe which has been used for soil moisture measurement (Gebregiorgis and Savage, 2006; Oguntunde and van de Giesen, 2005, Whalley et al., 2006, Goodger et al., 2005). It consists of a scaled polycarbonate rod with six pairs of stainless steel rings centered at 10, 20, 30, 40, 60 and 100 cm. After being inserted into an epoxy-fiberglass access tube, any pair of rings acts as the two plates of a capacitor that measures the voltage (mV) of ambient soil-tube system which can be converted into permittivity (Delta-T Devices Ltd., 2004). There are two approaches in converting permittivity measured by a capacitance probe into volumetric soil water content. One is to use the equation supplied by the manufacturer with default parameters; another is to apply the manufacturer's equation with parameters from the user's in situ calibration.

The manufacturer's equation is (Delta-T Devices Ltd., 2004):

$$\theta_v = \frac{\sqrt{\varepsilon} - a_0}{a_1} \qquad [1]$$

where, ε is the permittivity, θ_v is the volumetric water content cm^3 cm^{-3}. Parameters a_0 and a_1 are suggested to be 1.6 and 8.4 for mineral soil and 1.3 and 7.7 for organic soil by Delta-T Devices Ltd. Equation 1 is the same form and has very close coefficients (a_0=1.6 and a_1=8.1) for mineral soils with the equation in Gaskin and Miller (1996). The relationship between permittivity and output voltage was given by Delta-T Devices:

$$\sqrt{\varepsilon} = 1.125 - 5.53V + 67.17V^2 - 234.42V^3 + 413.56V^4 - 356.68V^5 + 121.53V^6 \qquad [2]$$

where V is the voltage output, vol.

Another approach is to calibrate onsite the equation provided by DeltaT Devices for each measurement location by different depths then use the calibrated equation to model soil moisture. Besides soil water content, size and shape of pores, concentration of dissolved electrolytes, and amount and composition of colloids have effect on soil dielectric constant with nearly equal significance (Chernyak, 1964). Soil structure, mineralogical composition and temperature also exert influence on the permittivity of soils (Chernyak, 1964; Baumhardt et al., 2000). So there is no a simple relationship between soil water content and permittivity. Dean et al. (1987) suggested that this relationship must be determined empirically by calibration, and this was also noted by Evett et al. (2006). Multisensor capacitance probes were calibrated in various soils under both laboratory and filed situations (Yoder et al., 1998; Morgan et al., 1999; Baumhardt et al., 2000; Evett et al., 2006; Polyakov et al., 2005; Kelleners et al., 2004). Results of specific calibration were quiet different from those provided by the factory (Evett et al., 2006). Baumhardt et al. (2000) showed that the factory-provided universal calibration equation estimated the water content for dry soils but not for saturated soils; Polyakov et al. (2005) found that the model offered by the manufacturer performed poorly at low water contents and could be largely improved by calibration, and laboratory calibration was significantly better than field calibration. Huang et al. (2004) documented that the PR1 probe had good accuracy in laboratory evaluation and a good function (r^2=0.87 RMSE=0.027 cm^3 cm^{-3}) was obtained by field calibration. Field calibration has been criticized for being costly and laborious in soil sampling for bulk density, but application of efficient engineering instruments such as a Giddings probe can facilitate and expedite field calibration.

The objectives of this study are 1) to determine the necessity of a field calibration by evaluating the performance of the equation supplied by the manufacturer for PR2 probe; and 2) to evaluate the performance of the onsite calibrated equations in predicting soil moisture.

Materials and Methods

Experimental Site

The field experimental plots were located near Gilmore City, Pocahontas County, IA, which is in the Des Moines Lobe. Predominant soils were Nicollet (fine-loamy, mixed, superactive, mesic Aquic Hapludoll) and Webster and Canisteo (fine-loamy, mixed, superactive, mesic Typic Endoaquolls) clay loams according to county level soil survey. Each plot was 0.05 ha (15.2 × 38 m). Drain tiles had been laid at a depth of 1.06 m parallel to the long dimension through the center of each plot and on the borders between plots with a spacing of 7.6 m. The flow rate of each plot had been monitored via the center tiles since 1989 consecutively. The detailed design of subsurface drainage system was described in Helmers et al. (2005) and Singh et al. (2006).

Thirty six access tubes were installed in 18 plots, noted as 1-18, with corn-soybean rotation, corn-soybean rotation with winter rye cover crop, pasture, and kura clover as the land covers. These 36 tubes were distributed in four soil types: Canisteo, Webster, Nicollet and Okboji. Two access tubes were installed in each of the 18 plots in October, 2005 for soil water content measurement using the PR2 probe. Of the two access tubes, one was installed in southern half and one in the northern half of the plot. Both were between the center drain tile and boundary tile lines, one was west and one east of the center line. The location for the access tube is noted by plot and location in the plot S or N. Installation was conducted with the kits and instruction supplied by Delta-T Devices. Soil samples were collected at 0-15, 15-30, and 30-60 cm in each plot for organic matter content analysis.

SW prediction by equations from DeltaT-default

The profile probe (PR2, Delta-T Devices Inc.) was inserted to each access tube on the same date as gravimetric soil sampling. Voltage output was recorded at 10, 20, 30, 40, 60 and 100 cm using an HH2 meter. Data were downloaded into a computer thereafter. Voltage was converted into permittivity by Eq. 2 for each depth.

Permittivity was input into DeltaT-default equation to obtain the predicted water content at 10, 20, 30, 40, and 60 cm. Default parameters for DeltaT-default equation were determined based on the result of organic matter content analysis. Predicted water content then was aggregated into soil water content at three depths, 0-15, 15-30, 30-60cm on weight basis.

Observed volumetric water content

Disturbed soil sample were extracted by a JMC soil sampler 60 to 100 cm away from the access tubes from depths ranging from 0-15 cm, 15-30 cm, and 30-60 cm biweekly in 2006 and weekly in 2007 during the crop growing season. The soil samples were placed in individual steel containers which were sealed for transport from the site to the Porous Media Lab, Agricultural and Biosystems Engineering Department of Iowa State University. Samples were dried at 105 ˚C for 72 hours to determine gravimetric water content.

To obtain soil bulk density, undisturbed soil cores were extracted by a truck mounted Giddings Probe (#25-SCS Model HDGSRPS, Giddings Machine Company Inc, CO) 1 meter away from each access tube on Nov. 9, 2006 and Nov. 19, 2007. Two Shelby tubes, 45 cm long each (18 in) with an inner diameter of 7.32 mm, were pushed vertically into the ground and pulled out one after another. Lubricate WD-40 was sprayed on the both sides of the Shelby tubes to reduce friction and compaction. In total, a 80 cm long soil core was obtained for each sampling location for the determination of soil bulk density. Soil cores were cut into the following depths: 5-15, 15-25, 25-35, 35-45 and 55-65 cm using a band saw. Soil cores were put in ovens at 105 ˚C for 96 hours to determine bulk density. The product of gravimetric water content multiplied by soil bulk density was considered as observed volumetric water content:

$$\theta_v = \theta_g \times \rho_b \qquad [3]$$

where θ_v is the volumetric water content, cm^3 cm^{-3}; θ_g is the gravimetric water content, g g^{-1}; and ρ_b is the bulk density, g cm^{-3}. The gravimetric samples were obtained at 0-15,15-30 and 30-60 cm, therefore the corresponding bulk density at these three depths, ρ_{b0-15}, ρ_{b15-30}, and ρ_{b30-60}, were aggregated from the bulk density at 5-15 (ρ_{b5-15}), 15-25 (ρ_{b15-25}), 25-35 (ρ_{b25-35}), 35-45 (ρ_{b35-45}) and 55-65 cm (ρ_{b55-65}). ρ_{b5-15} was considered as ρ_{b0-15}, and ρ_{b15-30} was the sum of 2/3 of ρ_{b15-25} and 1/3 of ρ_{b15-25}; ρ_{b30-60} was the sum of 1/5 of ρ_{b25-35}, 2/5 of ρ_{b35-45} and 2/5 of ρ_{b55-65}.

Field Calibration

Field calibration was conducted by fitting the observed volumetric water content against measured permittivity for each tube at each of the three depth increments, 0-15, 15-30 and 30-60cm. Equation 1 thereby was transformed into:

$$\theta_v = b_1\sqrt{\varepsilon} + b_0 \qquad [4]$$

Least square error method was employed to get best fits of b_0 and b_1. Coefficient of determination (r^2) was extracted for evaluating the goodness of fits. b_0 and b_1 values were calibrated using one year of field data from 2006 and two years of data from 2006+2007.

Calibrated equations using these two sets of data are noted as DeltaT-calibrated-2006 equations and DeltaT-calibrated-2006+2007 equations.

Statistical factors for performance evaluation

Four statistical factors noted by Singh et al. (2006) were adopted to evaluate the performance of all the equations in predicting soil moisture:

Root Mean Square Error, $RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(P_i - O_i\right)^2}$, [5]

Coefficient of Mass Residual, $CMR = \frac{\sum_{i=1}^{N} P_i - \sum_{i=1}^{N} O_i}{\sum_{i=1}^{N} O_i}$, [6]

Index of Agreement, $IoA = 1 - \frac{\sum_{i=1}^{N}\left(P_i - O_i\right)^2}{\sum_{i=1}^{N}\left(\left|O_i - \overline{O}\right| + \left|P_i - \overline{O}\right|\right)^2}$, [7]

and Model Efficiency, $EF = \frac{\sum_{i=1}^{N}\left(O_i - \overline{O}\right)^2 - \sum_{i=1}^{N}\left(P_i - O_i\right)^2}{\sum_{i=1}^{N}\left(O_i - \overline{O}\right)^2}$. [8]

Where *N* is the total number of the observations, P_i is the predicted volumetric water content of the ith observation, O_i is the observed volumetric water content of the ith observation, and $\overline{O}$ is the mean of the observed water content (*i* =1 to *N*). The predicted data fit the observed the best when RMSE, CMR, IoA and EF approach 0, 0, 1 and 1, respectively.

Results and Discussion

Soil Bulk Density and OM

The soil bulk density varied between 1.01 g cm^{-3} and 1.65 g cm^{-3}, lower at the upper depths and higher at the lower depths for most plots. The average values for 10, 20, 30, 40 and 60 cm were 1.26, 1.38, 1.41, 1.43 and 1.44 g cm^{-3}. The organic matter (OM) content ranged from 5.10 % to 1.10%. The average OM was 4.49%, 3.32% and 1.56% for the depth increments of 0-15, 15-30 and 30-60 cm, respectively. According to the User Manual for the Profile Probe (Delta-T Devices Ltd., 2004), soils with OM < 7% are defined as mineral soils. So the default a_0 and a_1 are 1.6 and 8.4 and the DeltaT-default equation (Eq.4) could be expressed as:

$$\sqrt{\varepsilon} = 0.528\theta_v - 0.146 \quad [9]$$

Observed water content and permittivity

Observed water content by soil sampling with paired PR2 reading were obtained from in total 31 days for 36 tubes at 3 depths, 11 days in 2006 and 20 days in 2007. The total 3348 pairs

(31days×36tubes×3depths) of data are included in Figure 1. The maxium observed volumetric water content was 0.490 $cm^3\ cm^{-3}$ in a soybean plot (14-3S) on April 2, 2007; the minimum observed water content was 0.078 $cm^3\ cm^{-3}$ in a corn plot (7-1S) on July 17, 2007. The standard deviation of observed soil water content were 0.067, 0.052 and 0.050 $cm^3\ cm^{-3}$ for the three depths at 0-15, 15-30, and 30-60cm respectively. Square root of permitivity ranged from 1.526 to 6.920 and the standard deviation for the three depths were 0.781, 0.876 and 0.809 respectively.

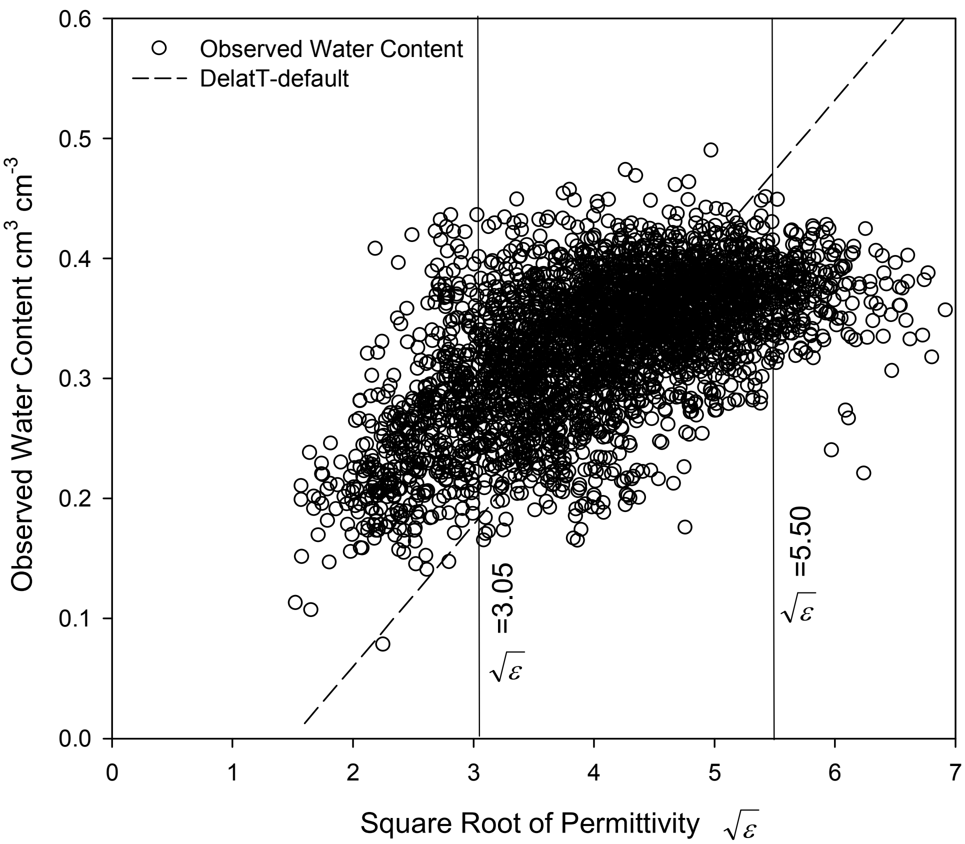


Figure 1. Square root of permittivity and observed volumetric water content

Performance of the DeltaT-default equation

As shown in Figure 1, the DeltaT-default equation consistently overestimated the soil water content at $\sqrt{\varepsilon}$ > 5.50 (voltage> 0.938 volt) but underestimated at $\sqrt{\varepsilon}$ < 3.05 (voltage<0.633 volt). Mwale et al. (2005) stated that the Profile Probe significantly overestimated water content in most cases, but in our study it occurred only when $\sqrt{\varepsilon}$ > 5.50.

Comparison of the predicted water content by the DeltaT-default equation with the observed water content was included in Figure 2. Predicted water content by the DeltaT-default equation had a wider range than the observed soil water content. The predicted water content by the DeltaT-default equation ranged from -0.009 to 0.634 $cm^3\ cm^{-3}$ while the observed water content ranged from 0.078 to 0.490 $cm^3\ cm^{-3}$ (Figure 2). The DeltaT-default equation overestimated the water content in the soil profile when the prediction was higher than 0.450 cm^3 cm^{-3} while underestimate the soil moisture when the prediction was lower than 0.150 cm^3 cm^{-3}. The prediction performance of the DeltaT-default equation in terms of statistical factors is listed in Table 1. On average across the land cover treatments, the lowest absolute value of CMR, highest IoA and EF were found in pasture plots. However, the overall statistical factors suggested an unsatisfactory prediction for each equation. The RMSE, CMR, IoA, and EF were 0.097 cm^3 cm^{-3}, -0.092, 0.674, and -1.625. The RMSE value was 29.6% of the observed mean soil water content (0.328 cm^3 cm^{-3}) and was much higher than the RMSE value, 0.027 cm^3 cm^{-3}, in Huang et al. (2004). High RMSE, negative EF and low coefficient of determination indicated the further calibration is needed for the PR2 probe.

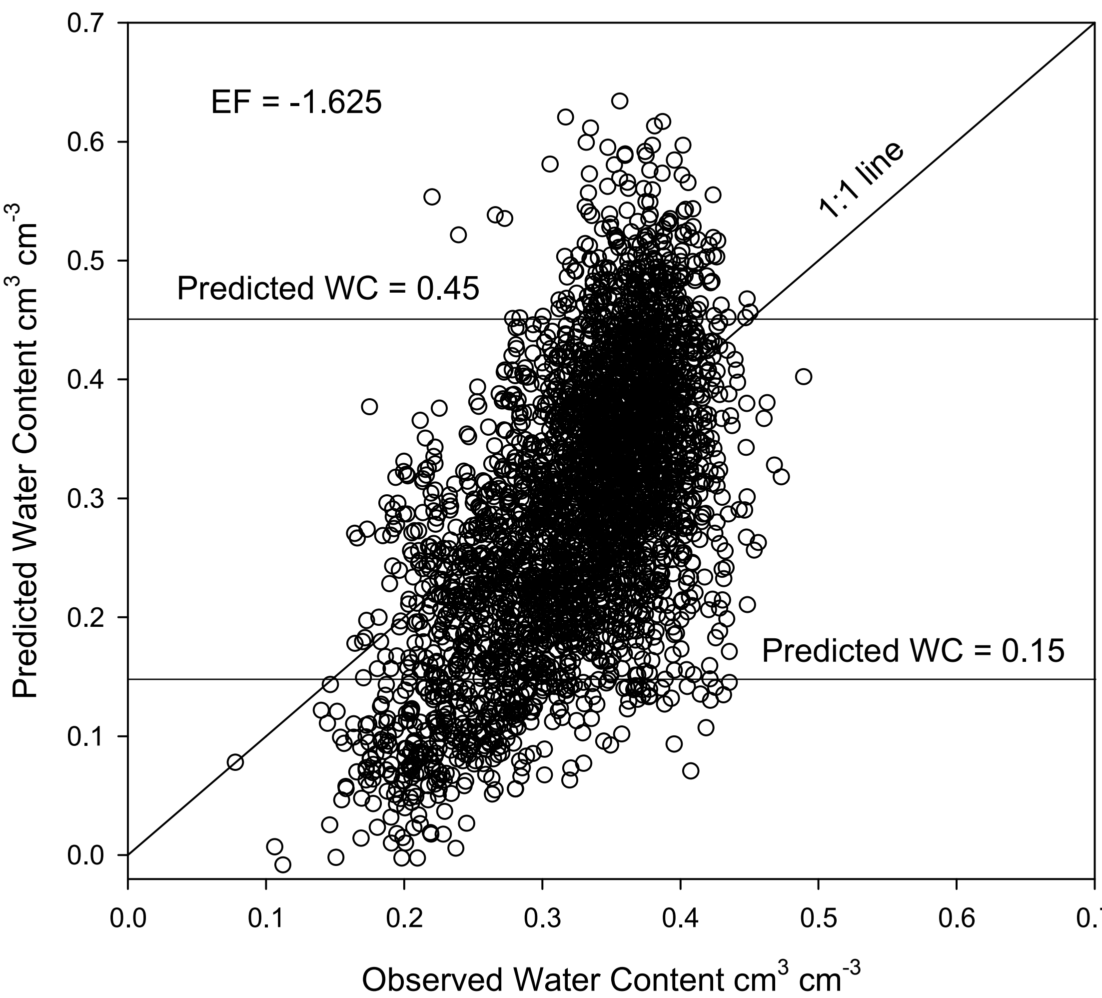


Figure 2. Observed water content in 2006 and 2007 and predicted water content using DeltaT-default equation

Table 1. Statistical factors of the comparison between the predicted water content by DeltaT-default equation and observed water content.

Treatment	Plot/ Location	RMSE	CMR	IoA	EF
Corn-Fallow-Soybean-Fallow	1 S	0.103	-0.145	0.631	-2.750
	1 N	0.136	-0.350	0.515	-5.768
	2 S	0.114	-0.275	0.536	-5.080
	2 N	0.087	-0.085	0.635	-1.944
	3 S	0.081	-0.108	0.730	-1.761
	3 N	0.138	-0.364	0.457	-5.797
Corn-Rye-Soybean-Rye	4 N	0.087	-0.180	0.664	-2.082
	4 S	0.095	-0.016	0.643	-2.109
	5 N	0.113	-0.148	0.606	-3.168
	5 S	0.114	-0.235	0.559	-4.275
	6 N	0.071	-0.026	0.678	-1.345
	6 S	0.073	-0.106	0.742	-1.209
Kura clover	7 S	0.105	-0.193	0.730	-1.767
	7 N	0.059	-0.125	0.814	-0.039
	8 N	0.062	-0.046	0.781	0.080
	8 S	0.082	0.005	0.696	-1.138
	9 S	0.075	-0.069	0.816	-0.505
	9 N	0.060	-0.056	0.830	0.005
Pasture	10 S	0.086	-0.021	0.824	-0.623
	10 N	0.073	0.016	0.845	-0.103
	11 S	0.077	0.129	0.800	-0.258
	11 N	0.086	0.092	0.741	-0.735
	12 N	0.067	0.082	0.825	-0.192
	12 S	0.072	0.093	0.823	-0.143
Soybean-Fallow-Corn-Fallow	13 S	0.086	-0.208	0.653	-1.891
	13 N	0.081	-0.060	0.754	-1.194
	14 S	0.102	-0.274	0.480	-3.661
	14 N	0.083	0.016	0.711	-1.066
	15 N	0.075	-0.071	0.737	-1.155
	15 S	0.100	-0.200	0.652	-1.679
Soybean-Rye-Corn-Rye	16 N	0.114	-0.096	0.642	-3.411
	16 S	0.146	-0.305	0.442	-8.009
	17 S	0.170	0.094	0.352	-13.854
	17 N	0.098	-0.017	0.663	-2.074
	18 S	0.104	0.081	0.620	-2.864
	18 N	0.092	-0.057	0.620	-2.494
Overall		0.097	-0.092	0.674	-1.625

Calibration

Since the statistical factors showed that DeltaT-default equation did not perform satisfactorily, new sets of b_0 and b_1 in Eq. 4 were obtained by fitting the observed water content against the square root of permittivity $\sqrt{\varepsilon}$ at the 3 different depths (0-15 cm, 15-30 cm, and 30-60 cm) in each location with a PR2 access tube. Calibrated b_0 and b_1 using the data from 2006 and 2006+2007 are included in Table 2 and Table 3. The calibrated parameters are different from the default parameters (b_0= -0.190, b_1=0.119) that are provided by the manufacturer. In Table 2, the calibrated coefficients b_0 ranged from -0.286 to 0.350, b_1 varied from -0.012 to 0.155 and the median of r^2 was 0.662; in Table 3, the calibrated coefficients b_0 ranged from -0.286 to 0.350, b_1 varied from -0.012 to 0.155 and the median of r^2 was 0.527. Coefficient of determination (r^2) decreases with the increase of depth. Arithmetical average of r^2 was 0.651, 0.645 and 0.437 in Table 2 and 0.603, 0.582, 0.274 in Table 3 for the depths of 0-15 cm, 15-30 cm and 30-60 cm, respectively.

Table 2. Fitted b_0, b_1 value and coefficient of determination (r^2) by data in 2006

Treatment	Notation	0-15 cm			15 -30 cm			30-60cm		
		b_0	b_1	r^2	b_0	b_1	r^2	b_0	b_1	r^2
Corn-Fallow-Soybean-Fallow	1 S	-0.043	0.129	0.447	0.384	-0.004	0.007	-0.093	0.108	0.513
	1 N	-0.010	0.120	0.359	0.056	0.076	0.695	-0.154	0.159	0.303
	2 S	0.020	0.093	0.611	0.229	0.029	0.187	0.343	0.002	0.001
	2 N	0.338	-0.003	0.000	-0.091	0.108	0.587	0.315	0.010	0.015
	3 S	0.073	0.069	0.671	0.151	0.042	0.600	0.287	0.013	0.075
	3 N	0.191	0.036	0.051	0.266	0.020	0.059	0.327	0.004	0.004
Corn-Rye-Soybean-Rye	4 N	**-0.067**	**0.125**	**0.785**	0.089	0.065	0.694	0.179	0.035	0.055
	4 S	**-0.205**	**0.186**	**0.772**	0.221	0.029	0.214	0.037	0.068	0.090
	5 N	-0.027	0.112	0.712	0.166	0.042	0.646	0.084	0.073	0.416
	5 S	**0.047**	**0.081**	**0.847**	**0.138**	**0.071**	**0.799**	0.145	0.051	0.433
	6 N	0.014	0.074	0.682	0.108	0.046	0.235	0.108	0.059	0.115
	6 S	-0.073	0.120	0.647	-0.045	0.087	0.754	0.483	-0.034	0.009
Kura clover	7 S	**0.050**	**0.072**	**0.910**	**0.137**	**0.045**	**0.865**	**0.125**	**0.061**	**0.801**
	7 N	**-0.008**	**0.081**	**0.821**	-0.251	0.144	0.733	-0.682	0.264	0.649
	8 N	**-0.002**	**0.074**	**0.847**	-0.389	0.183	0.742	-0.370	0.173	0.130
	8 S	**0.038**	**0.074**	**0.940**	**-0.123**	**0.107**	**0.844**	-0.822	0.266	0.672
	9 S	**0.069**	**0.066**	**0.951**	**0.096**	**0.057**	**0.927**	**-0.320**	**0.154**	**0.824**
	9 N	**0.005**	**0.079**	**0.943**	**-0.041**	**0.091**	**0.883**	-0.457	0.198	0.701
Pasture	10 S	**-0.008**	**0.076**	**0.966**	**0.062**	**0.058**	**0.964**	**0.020**	**0.067**	**0.864**
	10 N	**0.046**	**0.069**	**0.865**	**-0.017**	**0.078**	**0.792**	**-0.240**	**0.128**	**0.856**
	11 S	**-0.116**	**0.098**	**0.963**	**-0.222**	**0.116**	**0.919**	**-0.679**	**0.214**	**0.916**
	11 N	**-0.040**	**0.092**	**0.928**	**-0.250**	**0.126**	**0.805**	**-0.865**	**0.250**	**0.945**
	12 N	**-0.072**	**0.088**	**0.907**	**-0.206**	**0.112**	**0.917**	-0.582	0.200	0.707
	12 S	**-0.012**	**0.078**	**0.917**	**-0.181**	**0.110**	**0.958**	**-0.617**	**0.210**	**0.937**
Soybean-Fallow-Corn-Fallow	13 S	0.057	0.077	0.338	**-0.060**	**0.115**	**0.803**	-0.241	0.147	0.703
	13 N	0.000	0.083	0.714	0.110	0.058	0.610	0.104	0.051	0.131
	14 S	-0.026	0.115	0.579	-0.012	0.100	0.614	-0.081	0.107	0.317
	14 N	0.046	0.065	0.356	0.164	0.041	0.159	0.089	0.049	0.149
	15 N	0.205	0.025	0.042	0.197	0.034	0.559	0.085	0.060	0.460
	15 S	**-0.075**	**0.113**	**0.757**	0.005	0.108	0.510	0.143	0.045	0.414
Soybean-Rye-Corn-Rye	16 N	0.003	0.101	0.745	0.198	0.037	0.530	0.094	0.046	0.307
	16 S	0.147	0.059	0.236	**0.119**	**0.057**	**0.787**	0.071	0.056	0.569
	17 S	0.207	0.035	0.214	0.081	0.053	0.674	-0.133	0.108	0.631
	17 N	0.060	0.071	0.521	0.124	0.049	0.749	0.090	0.058	0.245
	18 S	**0.048**	**0.073**	**0.754**	0.050	0.064	0.620	-0.103	0.082	0.403
	18 N	0.059	0.080	0.653	**0.122**	**0.050**	**0.785**	0.108	0.048	0.387

Bold values are those b_0 and b_1 and r^2 with $r^2 \geq 0.750$.

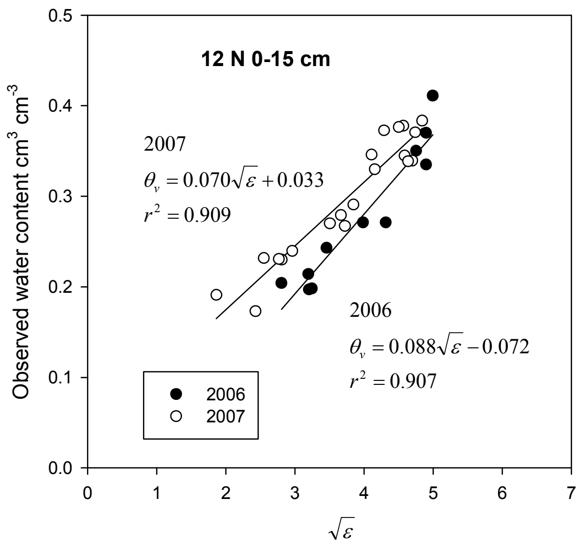
Table 3. Fitted b_0, b_1 value and coefficient of determination (r^2) by data in 2006+2007

Treatment	Notation	0-15 cm			15 -30 cm			30-60cm		
		b_0	b_1	r^2	b_0	b_1	r^2	b_0	b_1	r^2
Corn-Fallow-Soybean-Fallow	1 S	0.133	0.058	0.363	0.224	0.029	0.262	0.172	0.037	0.158
	1 N	0.112	0.068	0.509	0.128	0.056	0.724	0.138	0.066	0.258
	2 S	0.038	0.084	0.687	0.205	0.035	0.652	0.300	0.012	0.037
	2 N	0.208	0.034	0.243	0.091	0.058	0.575	0.275	0.017	0.086
	3 S	0.107	0.055	0.618	0.176	0.039	0.577	0.249	0.022	0.132
	3 N	0.105	0.064	0.371	0.202	0.036	0.256	0.340	-0.003	0.001
Corn-Rye-Soybean-Rye	4 N	**-0.038**	**0.112**	**0.748**	0.084	0.062	0.626	0.113	0.050	0.236
	4 S	0.088	0.074	0.485	0.122	0.048	0.721	0.179	0.038	0.234
	5 N	0.066	0.084	0.636	0.201	0.034	0.339	0.237	0.033	0.277
	5 S	0.095	0.071	0.613	0.261	0.030	0.508	0.202	0.035	0.402
	6 N	0.065	0.059	0.539	0.081	0.050	0.533	0.236	0.024	0.053
	6 S	0.050	0.075	0.588	0.080	0.057	0.663	0.208	0.032	0.083
Kura clover	7 S	**0.081**	**0.069**	**0.837**	**0.147**	**0.044**	**0.840**	**0.137**	**0.056**	**0.761**
	7 N	**0.026**	**0.073**	**0.858**	0.004	0.076	0.681	-0.286	0.155	0.355
	8 N	0.053	0.055	0.607	-0.013	0.088	0.656	0.249	0.018	0.015
	8 S	0.121	0.053	0.573	0.082	0.055	0.664	0.160	0.032	0.114
	9 S	**0.066**	**0.068**	**0.903**	**0.138**	**0.046**	**0.849**	0.041	0.065	0.480
	9 N	**0.034**	**0.067**	**0.800**	0.097	0.050	0.600	-0.193	0.125	0.488
Pasture	10 S	**0.010**	**0.077**	**0.863**	**0.106**	**0.052**	**0.880**	**0.121**	**0.043**	**0.783**
	10 N	**0.050**	**0.071**	**0.874**	**0.090**	**0.054**	**0.761**	-0.037	0.079	0.729
	11 S	**-0.008**	**0.077**	**0.753**	**-0.024**	**0.069**	**0.812**	-0.262	0.118	0.710
	11 N	**0.003**	**0.082**	**0.846**	-0.019	0.070	0.732	-0.231	0.107	0.616
	12 N	**0.010**	**0.073**	**0.836**	**0.047**	**0.057**	**0.758**	-0.156	0.103	0.472
	12 S	**-0.005**	**0.079**	**0.887**	**0.019**	**0.062**	**0.818**	-0.159	0.099	0.602
Soybean-Fallow-Corn-Fallow	13 S	0.084	0.069	0.528	0.115	0.063	0.667	0.025	0.079	0.487
	13 N	0.075	0.066	0.679	0.204	0.036	0.619	0.170	0.037	0.185
	14 S	0.100	0.066	0.435	0.149	0.049	0.374	0.329	-0.012	0.013
	14 N	0.098	0.049	0.361	0.162	0.040	0.254	0.237	0.021	0.090
	15 N	0.155	0.041	0.268	0.220	0.030	0.390	0.213	0.034	0.120
	15 S	0.040	0.074	0.453	0.247	0.030	0.210	0.130	0.046	0.405
Soybean-Rye-Corn-Rye	16 N	0.070	0.077	0.652	0.181	0.042	0.475	0.248	0.019	0.180
	16 S	0.132	0.062	0.384	0.187	0.045	0.431	0.350	0.002	0.007
	17 S	0.275	0.021	0.064	0.202	0.028	0.404	0.344	0.001	0.001
	17 N	0.090	0.072	0.547	0.177	0.039	0.525	0.187	0.036	0.252
	18 S	0.067	0.068	0.696	0.121	0.048	0.428	0.248	0.018	0.047
	18 N	0.083	0.069	0.591	0.104	0.053	0.708	0.305	0.003	0.001

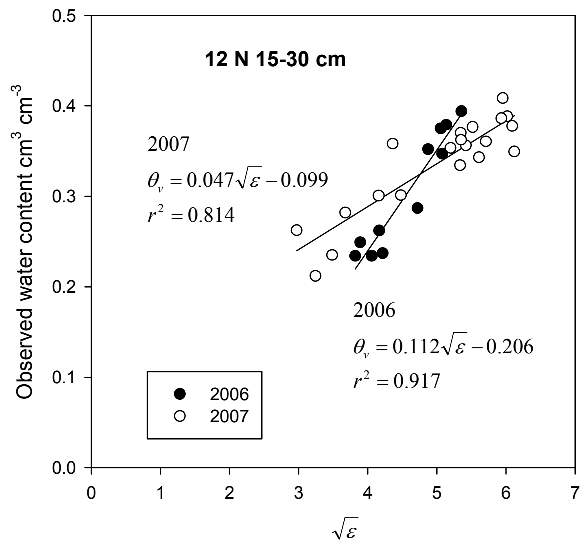
Bold values are those b_0 and b_1 and r^2 with $r^2 \geq 0.750$.

Kura Clover and Pasture plots indicated better calibration fitting. Bold values are those b_0, b_1 and r^2 with $r^2 \geq 0.750$. In the calibration equations included in Table 2, for the depth at 0-15 cm $r^2 \geq 0.750$ was obtained at 17 locations; for the depth at 15-30 cm, there were 14 locations with $r^2 \geq 0.750$; for the depth at 30-60 cm, it reduced to 7 locations with $r^2 \geq 0.750$. Among all the fits with $r^2 \geq 0.750$ in Table 2, 34% were from Kura clover plots and 42% from Pasture plots. In Table 3, locations with $r^2 \geq 0.750$ were 11, 7 and 2 for the three depths respectively, among which 35% were from Kura clover plots and 60% from Pasture plots.

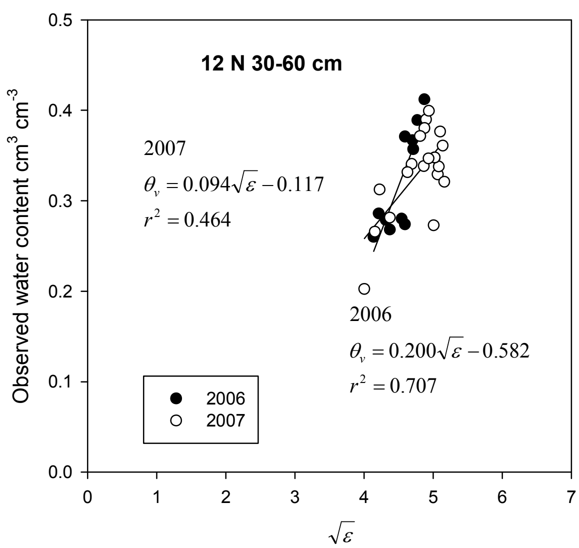
Slopes of the calibration equation at each depth showed different patterns in 2006 and 2007. At 0-15 cm, twenty seven among 36 calibration equations had steeper slopes in 2006 than in 2007; at 15-30 and 30-60 cm, the number of calibration equations with a steeper slope were 27 and 30, respectively. As shown in Figure 3, at the access tube 12-N, slopes of calibrated equations in 2006 were 0.088, 0.112 and 0.200 while in 2007 were 0.071, 0.047 and 0.094 for the 3 depths respectively.



(a)



(b)



(c)

Figure 3. Patterns of calibration equations in 2006 and 2007 at 3 depths: a) 0-15 cm, b) 15-30 cm, and c) 30-60 cm

DeltaT-calibrated-2006 Equations, with calibrated b_0 and b_1 from 2006 data (Table 2), were used to predict the soil moisture in 2006 and 2007 at three depths. The predicted versus observed soil moisture were plotted in Figure 4 and the general statistical factors over 3 depths for each access tube are included in Table 4. Overall RMSE, CMR, IoA and EF for all tubes at all depths were 0.032 $cm^3\ cm^{-3}$, 0, 0.927 and 0.756 when predicting soil moisture in 2006. EF values were higher in Kura Clover and Pasture plots. Predicted soil moisture in 2007 showed more differences from observed values than that in 2006. The statistical factors were 0.062 $cm^3\ cm^{-3}$, 0.051, 0.755 and -0.239. EF values showed higher variability. If using b_0 and b_1 in Table 2 to predict soil moisture in 2006+2007, the statistical factors indicated a medium performance between 2006 and 2007.

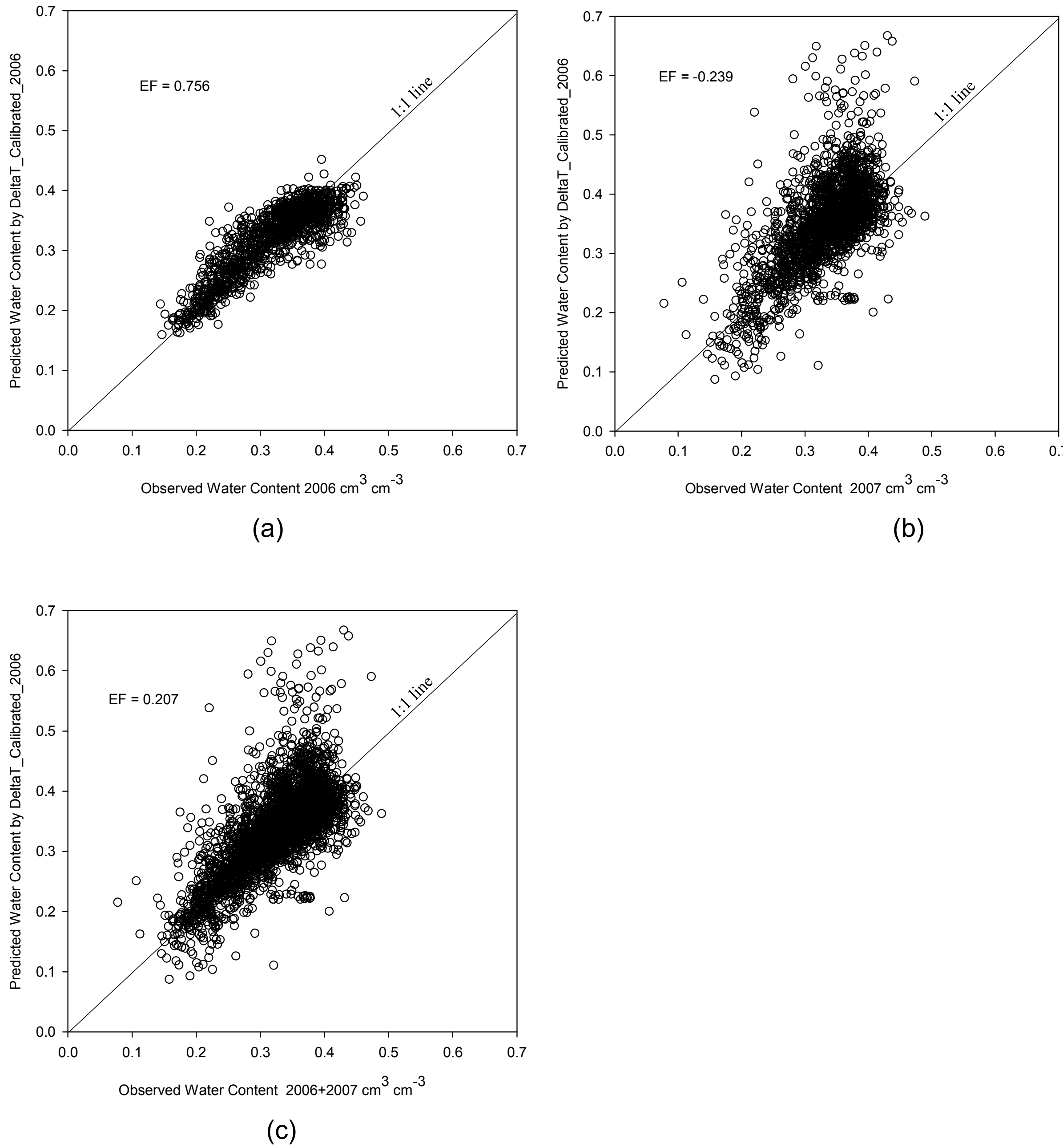


Figure 4. Comparison of observed water content with water content predicted by DeltaT-calibrated-2006 Equations in a) 2006, b)2007 and c)2006+2007.

Table 4. Statistical factors for the comparison of predicted soil water content by DeltaT-calibrated-2006 equations with observed soil water content

Treatment	Notation	General over 3 depths 2006				General over 3 depths 2007				General over 3 depths 2006+2007			
		RMSE	CMR	IoA	EF	RMSE	CMR	IoA	EF	RMSE	CMR	IoA	EF
Corn-Fallow-Soybean-Fallow	1 S	0.038	0.000	0.831	0.532	0.070	0.114	0.593	-0.817	0.060	0.073	0.652	-0.286
	1 N	0.037	0.000	0.841	0.557	0.050	0.081	0.808	0.028	0.046	0.053	0.818	0.237
	2 S	0.031	0.000	0.818	0.513	0.030	0.031	0.874	0.608	0.030	0.020	0.858	0.577
	2 N	0.044	0.000	0.574	0.215	0.062	0.073	0.634	-0.500	0.057	0.048	0.628	-0.256
	3 S	0.031	0.000	0.890	0.665	0.027	-0.003	0.869	0.629	0.029	-0.002	0.882	0.652
	3 N	0.045	0.000	0.663	0.284	0.044	0.024	0.615	0.289	0.045	0.016	0.640	0.289
Corn-Rye-Soybean-Rye	4 N	0.025	0.000	0.925	0.752	0.033	0.048	0.863	0.537	0.030	0.032	0.890	0.621
	4 S	0.027	0.000	0.888	0.658	0.113	0.166	0.503	-2.937	0.092	0.109	0.562	-1.974
	5 N	0.030	0.000	0.895	0.678	0.048	0.027	0.806	0.266	0.042	0.018	0.838	0.417
	5 S	0.022	0.000	0.934	0.776	0.056	0.055	0.772	-0.221	0.047	0.036	0.816	0.121
	6 N	0.028	0.000	0.866	0.608	0.038	0.026	0.780	0.349	0.035	0.017	0.811	0.439
	6 S	0.030	0.000	0.896	0.677	0.046	0.072	0.796	0.044	0.041	0.047	0.832	0.311
Kura clover	7 S	0.023	0.000	0.968	0.883	0.032	-0.032	0.929	0.678	0.029	-0.022	0.948	0.790
	7 N	0.033	0.000	0.927	0.760	0.053	0.080	0.816	-0.141	0.047	0.053	0.865	0.344
	8 N	0.044	0.000	0.884	0.649	0.077	0.135	0.684	-0.963	0.067	0.090	0.780	-0.088
	8 S	0.029	0.000	0.950	0.823	0.124	0.193	0.378	-6.771	0.101	0.128	0.563	-2.289
	9 S	0.022	0.000	0.977	0.913	0.048	0.036	0.818	0.045	0.040	0.024	0.902	0.562
	9 N	0.029	0.000	0.957	0.847	0.060	0.140	0.752	-0.485	0.051	0.093	0.849	0.265
Pasture	10 S	0.017	-0.001	0.986	0.946	0.040	-0.042	0.922	0.603	0.034	-0.028	0.945	0.752
	10 N	0.029	0.000	0.957	0.845	0.048	0.036	0.891	0.442	0.042	0.024	0.917	0.627
	11 S	0.020	0.000	0.983	0.936	0.072	0.046	0.816	-0.407	0.059	0.031	0.874	0.268
	11 N	0.022	-0.001	0.972	0.895	0.071	0.097	0.806	-0.313	0.058	0.064	0.856	0.195
	12 N	0.024	0.000	0.965	0.872	0.061	0.020	0.842	-0.125	0.051	0.013	0.878	0.310
	12 S	0.019	0.000	0.984	0.938	0.074	0.116	0.788	-0.502	0.060	0.077	0.857	0.192
Soybean-Fallow-Corn-Fallow	13 S	0.042	0.000	0.847	0.562	0.047	0.076	0.800	-0.279	0.045	0.050	0.826	0.206
	13 N	0.034	0.000	0.913	0.719	0.034	-0.010	0.902	0.464	0.034	-0.006	0.909	0.611
	14 S	0.035	0.000	0.835	0.547	0.062	0.114	0.642	-1.051	0.054	0.075	0.718	-0.300
	14 N	0.050	0.000	0.792	0.465	0.038	0.006	0.796	0.410	0.043	0.004	0.801	0.450
	15 N	0.034	0.000	0.860	0.592	0.035	-0.026	0.817	0.455	0.035	-0.017	0.840	0.535
	15 S	0.032	0.000	0.935	0.781	0.067	0.094	0.757	-0.358	0.057	0.062	0.817	0.138
Soybean-Rye-Corn-Rye	16 N	0.032	0.000	0.913	0.721	0.037	-0.039	0.853	0.457	0.035	-0.026	0.878	0.579
	16 S	0.041	0.000	0.840	0.550	0.082	-0.136	0.323	-3.556	0.070	-0.089	0.507	-1.088
	17 S	0.033	0.000	0.798	0.472	0.128	0.178	0.272	-7.641	0.105	0.116	0.350	-4.598
	17 N	0.038	0.000	0.851	0.585	0.049	-0.029	0.790	0.192	0.045	-0.019	0.809	0.349
	18 S	0.036	0.000	0.884	0.650	0.045	0.021	0.767	0.160	0.042	0.013	0.817	0.387
	18 N	0.029	0.000	0.883	0.644	0.044	0.062	0.747	0.178	0.040	0.040	0.793	0.344
Overall		0.032	0.000	0.927	0.756	0.062	0.051	0.755	-0.239	0.053	0.033	0.818	0.207

Another set of equations, DeltaT-calibrated-2006+2007 were developed using all the data. These equations based on 2006+2007 data, which are included in Table 3, were used to predict soil moisture in 2006, 2007, and 2006+2007. Predicted soil moisture against observed values are plotted in Figure 5 and the statistical factors are shown in Table 5. The overall RMSE between predicted and observed soil moisture was 0.039 for 2006, 0.031 for 2007 and 0.034 for 2006+2007, which are acceptable according to field experiments conducted by Huang et al (2004). Overall average CMR were between -0.007 and 0.004, IoA were between 0.877 and 0.977, and EF was greater than 0.654. RMSE values of corn soybean rotation fallowed in winter were higher on average than any other treatments.

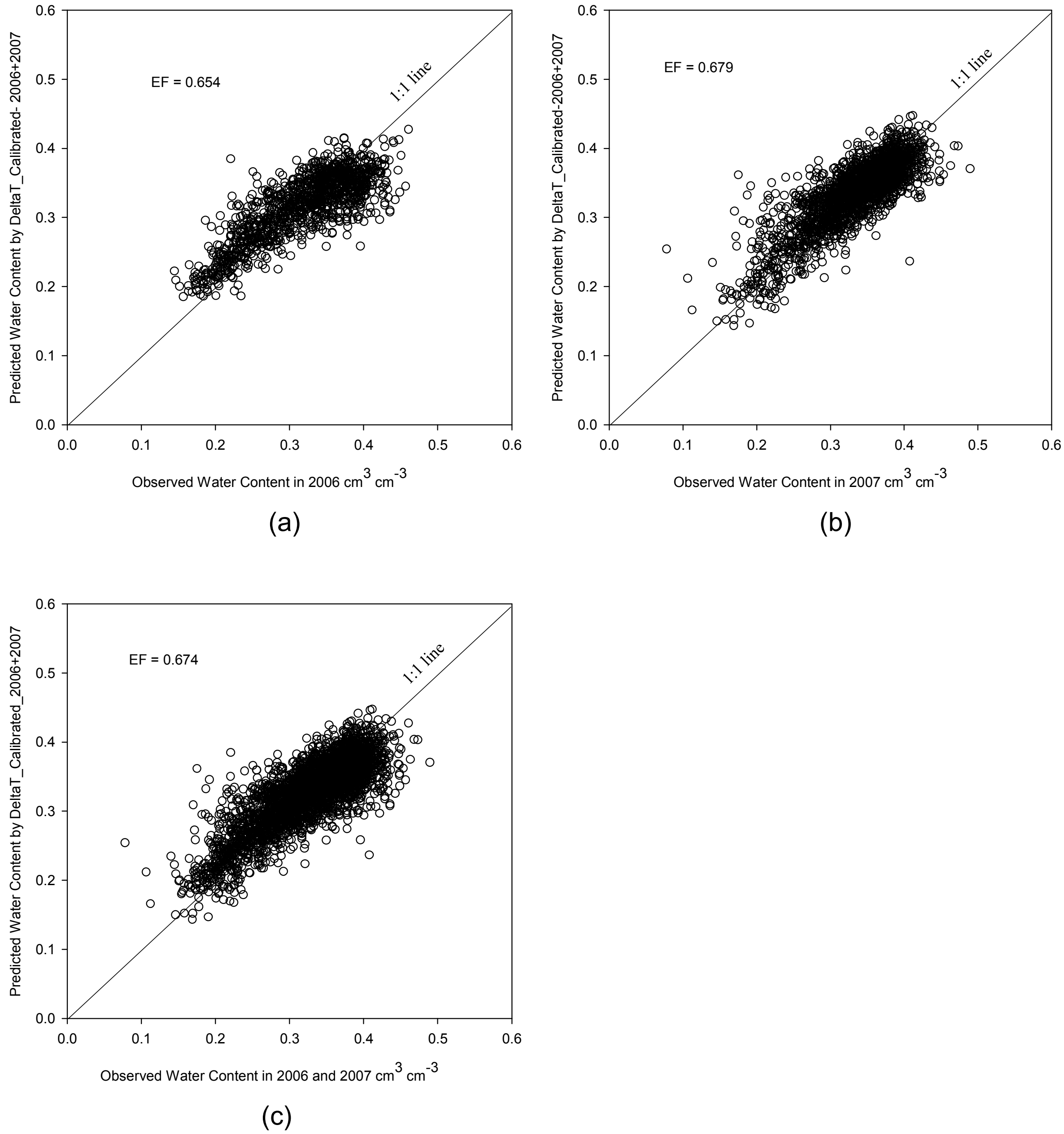


Figure 5. Comparison of observed water content with water content predicted by DeltaT-calibrated-2006+2007 Equations in a) 2006, b)2007 and c)2006+2007.

Table 5. Statistical factors for the comparison of predicted soil water content by DeltaT-calibrated-2006+2007 equations with observed soil water content.

Treatment	Notation	General over 3 depths 2006				General over 3 depths 2007				General over 3 depths 2006+2007			
		RMSE	CMR	IoA	EF	RMSE	CMR	IoA	EF	RMSE	CMR	IoA	EF
Corn-Fallow-Soybean-Fallow	1 S	0.047	-0.049	0.712	0.266	0.036	0.028	0.822	0.529	0.040	0.000	0.774	0.433
	1 N	0.040	-0.030	0.786	0.465	0.028	0.016	0.906	0.703	0.033	0.000	0.866	0.610
	2 S	0.032	-0.022	0.802	0.467	0.026	0.012	0.901	0.698	0.028	0.000	0.872	0.623
	2 N	0.049	-0.052	0.502	0.014	0.036	0.028	0.784	0.510	0.041	0.000	0.705	0.343
	3 S	0.032	0.005	0.881	0.631	0.023	-0.002	0.917	0.739	0.027	0.000	0.904	0.698
	3 N	0.047	-0.036	0.683	0.213	0.040	0.020	0.711	0.415	0.043	0.000	0.707	0.344
Corn-Rye-Soybean-Rye	4 N	0.027	-0.032	0.900	0.693	0.028	0.017	0.895	0.683	0.027	0.000	0.902	0.692
	4 S	0.041	-0.041	0.734	0.198	0.036	0.022	0.844	0.613	0.038	0.000	0.818	0.510
	5 N	0.033	0.002	0.846	0.626	0.040	-0.001	0.809	0.474	0.038	0.000	0.825	0.535
	5 S	0.028	-0.005	0.868	0.662	0.034	0.003	0.844	0.546	0.032	0.000	0.856	0.591
	6 N	0.029	-0.010	0.842	0.585	0.035	0.005	0.783	0.447	0.033	0.000	0.806	0.496
	6 S	0.034	-0.032	0.845	0.581	0.027	0.017	0.892	0.663	0.030	0.000	0.878	0.632
Kura clover	7 S	0.027	0.027	0.952	0.837	0.024	-0.013	0.953	0.820	0.025	0.000	0.956	0.844
	7 N	0.039	-0.011	0.862	0.662	0.027	0.006	0.917	0.695	0.032	0.000	0.902	0.691
	8 N	0.050	0.008	0.828	0.543	0.035	-0.003	0.870	0.600	0.041	0.000	0.861	0.600
	8 S	0.046	-0.001	0.782	0.549	0.036	0.000	0.805	0.363	0.040	0.000	0.816	0.497
	9 S	0.030	0.002	0.947	0.834	0.026	-0.001	0.926	0.725	0.027	0.000	0.942	0.801
	9 N	0.039	-0.047	0.894	0.719	0.031	0.024	0.878	0.599	0.034	0.000	0.894	0.673
Pasture	10 S	0.026	0.041	0.959	0.863	0.023	-0.021	0.968	0.872	0.024	0.000	0.965	0.873
	10 N	0.036	0.000	0.920	0.768	0.027	0.000	0.953	0.821	0.030	0.000	0.944	0.807
	11 S	0.040	0.014	0.898	0.742	0.029	-0.007	0.943	0.768	0.033	0.000	0.929	0.765
	11 N	0.034	-0.008	0.906	0.748	0.030	0.004	0.936	0.763	0.032	0.000	0.929	0.764
	12 N	0.036	0.018	0.884	0.707	0.028	-0.010	0.939	0.763	0.031	0.000	0.923	0.747
	12 S	0.036	-0.017	0.916	0.770	0.028	0.010	0.944	0.784	0.031	0.001	0.936	0.785
Soybean-Fallow-Corn-Fallow	13 S	0.046	-0.021	0.755	0.469	0.022	0.011	0.920	0.712	0.033	0.000	0.857	0.586
	13 N	0.038	0.018	0.868	0.663	0.024	-0.010	0.931	0.731	0.030	0.000	0.907	0.706
	14 S	0.043	-0.021	0.639	0.337	0.031	0.011	0.803	0.481	0.036	0.000	0.762	0.429
	14 N	0.051	0.002	0.774	0.450	0.035	-0.002	0.819	0.506	0.041	0.000	0.802	0.489
	15 N	0.035	0.015	0.857	0.557	0.032	-0.008	0.832	0.547	0.033	0.000	0.851	0.574
	15 S	0.037	-0.013	0.894	0.704	0.038	0.007	0.858	0.569	0.037	0.000	0.874	0.629
Soybean-Rye-Corn-Rye	16 N	0.034	0.019	0.893	0.675	0.028	-0.010	0.906	0.691	0.030	0.000	0.901	0.688
	16 S	0.047	0.018	0.785	0.401	0.028	-0.010	0.775	0.477	0.036	0.000	0.786	0.456
	17 S	0.040	0.010	0.476	0.195	0.041	-0.006	0.508	0.102	0.041	0.000	0.491	0.146
	17 N	0.044	0.023	0.774	0.439	0.035	-0.012	0.848	0.571	0.039	0.000	0.820	0.521
	18 S	0.039	-0.001	0.832	0.576	0.035	0.001	0.812	0.476	0.037	0.000	0.822	0.525
	18 N	0.033	-0.028	0.826	0.536	0.035	0.015	0.811	0.504	0.034	0.000	0.816	0.515
Overall		0.039	-0.007	0.877	0.654	0.031	0.004	0.901	0.679	0.034	0.000	0.895	0.674

In order to show the prediction performance of DeltaT-calibrated-2006+2007 equations, a location with medium improvement, 16 N, was selected to demonstrate the prediction efficiency. Location 16 N was selected because at this location the values of four statistical factors over 3 depths in 2006+2007, 0.030 $cm^3\ cm^{-3}$, 0.000, 0.895, and 0.674, were close to the overall average values (Table 7). Soil water content predicted by the DeltaT-default equation and DeltaT-calibrated-2006+2007 equations for location 16 N were compared with the observed water content in Figure 6. In comparison with the observed water content, the predicted water content by DeltaT-default equation at 16 N showed RMSE values 0.089, 0.030 and 0.041 $cm^3\ cm^{-3}$ at 0-15, 15-30, and 30-60 cm depths, respectively; while the RMSE values decreased to 0.015, 0.016 and 0.018 $cm^3\ cm^{-3}$ for the soil water content predicted by DeltaT-calibrated-2006+2007 equations.

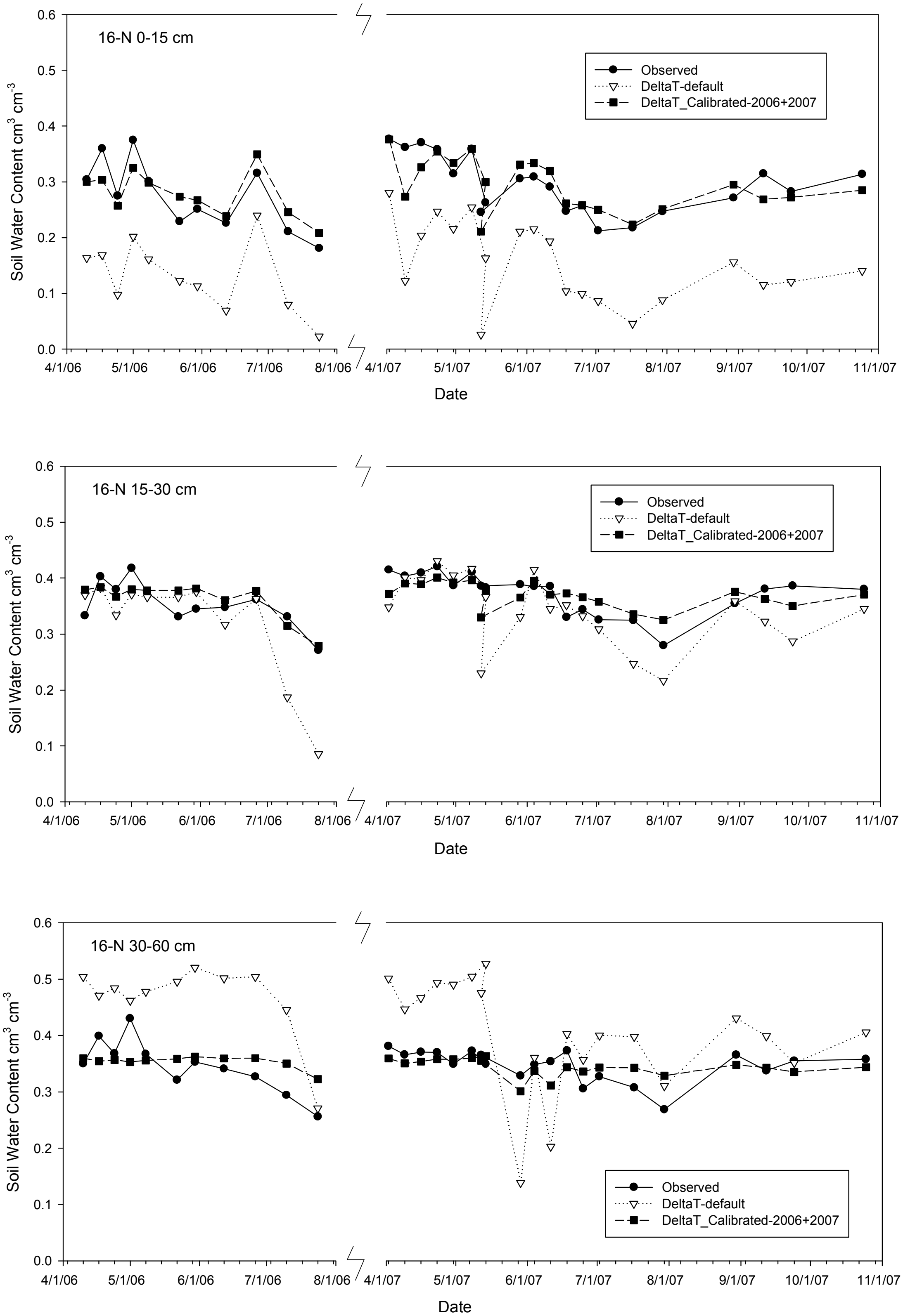


Figure 6. Comparison of observed water content with water content predicted by DeltaT-default and DeltaT-calibrated-2006+2007 Equations.

Summary and Conclusion

Multisensor capacitance probes have been considered as an alternative for neutron scattering gage because of their advantage to human health. However, the accuracy and the necessity of field calibration for these probes are concerned by users. For the PR2 Profile probe, the equation with default parameters provided by the manufacturer (DeltaT-default equation) generally predicted the water content at large errors in Des Moines Lobe soils. The overall RMSE, CMR, IoA, and EF were 0.097 $cm^3\ cm^{-3}$, -0.092, 0.674, and -1.625. A field calibration was necessary for the PR2 Profile probe. Equations calibrated from a one-year dataset (DeltaT-calibrated-2006 equations) improved those four statistical factors to 0.032 $cm^3\ cm^{-3}$, 0.000, 0.927 and 0.756 if applied to predict soil moisture in 2006, but if using DeltaT-calibrated-2006 Equations to predict soil moisture in 2007, the statistical factors were 0.062 $cm^3\ cm^{-3}$, 0.051, 0.755 and -0.239. Using the equations calibrated from a two-year dataset (DeltaT-calibrated-2006+2007 equations) resulted in close prediction to observed soil moisture for both 2006 and 2007. The overall four statistical factors were 0.039 $cm^3\ cm^{-3}$, -0.007, 0.877, 0.654 for 2006 and 0.031 $cm^3\ cm^{-3}$, 0.004, 0.901 and 0.679 for 2007. The RMSE values resulted by the prediction of DeltaT-calibrated-2006+2007 were comparable to the RMSE value (0.027 $cm^3\ cm^{-3}$) from the literature using the Profile probe (Huang et al., 2004).

Calibrated parameters, b_0 and b_1, showed a lower variability in plots without or with little soil disturbance such as Pasture and Kura clover plots. Calibration equations for access tubes located in Pasture and Kura clover field generally had a higher coefficient of determination than those in corn-soybean rotation plots. Statistical factors in Pasture and Kura clover plots suggested better performance of soil moisture prediction than that in other plots.

The results indicated that DeltaT-calibrated-2006 equations predicted the soil moisture in 2007 large RMSE and low model efficiency (EF), while DeltaT-calibrated-2006+2007 equations improved the prediction largely. From this data set there seemed to be some benefit of using a longer period of data for the PR2 probe calibration.

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